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Water is the vessel through which we ride the waves of changing climates

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Acting through water, climate change may affect livelihoods, societal structures, and political conflicts, hindering progress toward poverty reduction. Expanding on themes from the WEST Water Conference, this perspective paper considers how water insecurity from changing climates has unequal impacts within societies, water and gender roles, changing livelihoods, and shifting cultural norms. Opportunities are shared to build resilience into our future water systems. First, technologies are considered for tracking water availability, quality, and usage. Second, collaborating with nature to manage water builds into the idea of blue-green cities. And third, the route to community participation in managing resilient water systems is with an empowered population, made possible through a three-step process of Awareness, Education, and Resources.

KEYWORDS

water insecurity, public health, climate change, environmental policy, community participation, drinking water, sanitation

1 Introduction

The United Nations reported that 720 million people (10% of the global population) lived in high-or critically-water stressed countries (U.N. Water, 2024) and that 3.2 billion people lived in agricultural areas with high water shortages (Food and Agriculture Organizations of the United Nations, 2020). Meanwhile, the Intergovernmental Panel on Climate Change (IPCC) reported that global warming will increase the number of areas affected by agricultural and ecological droughts (Intergovernmental Panel on Climate Change, 2023). Changing climates affect water resources worldwide, with repercussions for environmental and public health. It has been said that "*If climate change is a shark, then water is its teeth*"; it is through water that we feel the effects of changing climates. In this perspective paper, we link changing climates with water (in)security and share recommendations and success stories toward creating equitable and climate-resilient water futures.

This perspective paper builds on discussions from the 2022 Water and Environment Student Talks (WEST, Vancouver, Canada) Conference hosted by students at the University of British Columbia and University of Victoria. Student researchers and water experts from 25 countries united for 3 days of virtual discussions. A predominant theme was that climate change is affecting how people interact with their surroundings and with each other, and that water is the medium through which we feel these effects. This paper highlights the human-water interactions in a changing climate.

2 Changing climates create worldwide waves

Climate change, population growth, and rapid economic development pressure water resources, resulting in 739 million children being exposed to high water scarcity in 2022 (United Nations Children's Fund, 2023). Water scarcity occurs when demand exceeds supply due to physical or economic factors (UN Water and Food and Agriculture Organization of the United Nations, 2007). The water crisis was listed in the top five "high impact risks" by the World Economic Forum eight times between 2012 and 2020 (World Economic Forum, 2020) as cities like Melbourne (2006–09), São Paulo (2015), Cape Town (2018), and Mexico City (2024) neared "day zero" of running out of water. Terrestrial water reservoirs have been declining by 1 cm/year over the past two decades (World Meteorological Organization, 2024), and Famiglietti and Rodell (2013) summarized changing climates on water resources as, "wet areas to get wetter, and dry areas to get drier."

Drought often leads to increased reliance on groundwater, but without sustainable management, it risks overexploitation. Famiglietti[1] explained, "*Drought accelerates and exposes the problems and there is an over-reliance on groundwater during drought which is dangerous because it is such an important buffer for resilience.*" In addition to jeopardizing water access, groundwater extraction is a leading factor of land subsidence (Davydzenka et al., 2024) up to 25 cm/year and implications for structural foundations, roadways, and aqueducts as seen in California, Mexico City, Iran, and the northeastern China plains (Motagh et al., 2008; Herrera-García et al., 2021). Amidst these long-term trends, acute weather events are more frequent (Aghakouchak et al., 2020): since the 1970s, the 20-and 50-year flooding frequency has increased in temperate zones worldwide (Slater et al., 2021). Meanwhile, Hirabayashi et al. (2013) concluded that flood frequency may increase in 42% of the globe (South/Southeast Asia, eastern and low-latitude Africa, South America) and decrease in another 18% (eastern Europe, Türkiye, central North America). Extreme weather affects source water quality for example through washing away anthropogenic wastes during floods (e.g., feces, hydrocarbons, nitrates, etc.), turbidity from landslides following forest fires, eutrophication following algal blooms from high temperatures (e.g., dissolved oxygen, cyanotoxins, pH), all of which impairs its treatability by existing water infrastructure (Zou et al., 2023).

Certain countries may have the resources to adapt to new water sources or changing water use patterns. However, the impacts of climate change are felt at an individual level, with repercussions for public health, famine, livelihoods, and culture. In many cases, water is the messenger delivering the hardships of changing climates. Protracted droughts may lead to famine or an increased burden of disease from insufficient water for sanitation and hygiene. As a creeping phenomenon, the impacts of drought are tougher to characterize but may include respiratory complications from dust, pollen, and particulate matter ($PM_{2.5}$) (Barnes, 2018), zoonotic diseases from the co-habitation of humans with livestock (Matthew et al., 2022), and deteriorating mental health (Vins et al., 2015). Conversely, floods may destroy crops and livelihoods while facilitating the spread of cholera, typhoid, zika, and water-related diseases (Du et al., 2010).

1 Quoted speaker affiliations:
The following water experts were involved in panels or as keynote speakers at the 2022 WEST Conference, and whose ideas from the event were quoted in this article:
Jay Famiglietti is professor at the School of Environment and Sustainability. University of Saskatchewan and Executive Director of the Global Institutes for Water Security.

3 Societal ripples from changing water patterns

"*Climate action and a sustainable water future are two sides of the same coin,*" spoke UN Secretary-General Antonio Guterres before describing the 2023 UN-Water Conference as "*A conference on today's world, seen through the perspective of its most valuable resource.*"

3.1 Water in social structures

Certain populations are disproportionately affected by unsafe water. In Canada, First Nations communities were 2.5 times more likely to receive boil water advisories than non-First Nations communities (Patrick, 2011). In California, demographics such as income, race, and ethnicity were linked to water service and quality violations, with rural areas facing more health-based violations than urban ones (Allaire et al., 2018). Systems serving severely disadvantaged and Latino communities had more violations, though low-income violations have decreased over time (Allaire and Acquah, 2022). A 2011 Michigan study found water costs higher in areas with larger racial minority populations due to decaying infrastructure (Butts and Gasteyer, 2011). In Nepal, household water expenses varied by district, education level, and water insecurity index, with the poorest paying the highest marginal cost (Figure 1; Shrestha et al., 2018). Interestingly, households' relative monthly expenses on water increased with education level, leading those authors to suggest that increasing awareness of water challenges and opportunities leads to people placing a great financial value on safe water.

3.2 Water and gender

In many regions, women manage household water for cooking, cleaning, and sanitation, while men use it for income-generating activities. Women often prioritize their families' needs over their own, leading to insufficient water for themselves, especially during droughts (Wutich, 2009). A study in sub-Saharan Africa found women may face violence when they cannot provide enough water for their families (Pommells et al., 2018), while 2,000 women in Uganda, Kenya, and Ghana reported water-or sanitation-related violence (Elliot, 2022). Although responsible for water collection, women can have unequal participation in water governance, influenced by age, marital status, education, and socio-economic position (Sultana, 2009). Globally and especially in East Africa, attitudes are shifting toward understanding the importance of involving women in water governance, even among men (Hannah et al., 2021; Zimmermann et al., 2023). This change is supported by policies like Kenya's mandate for gender-balanced water committees (The People of Kenya, 2010). Yet anecdotally, a majority of community leaders and water committee chairs remain men (Figure 2).

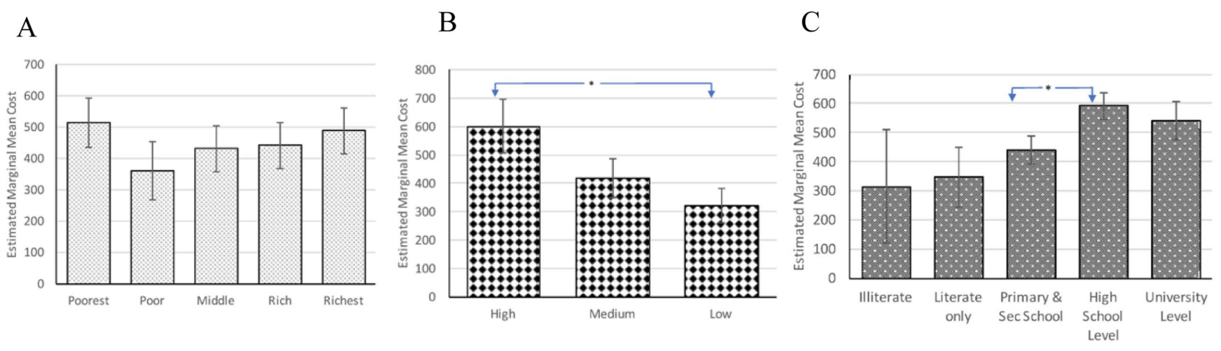

FIGURE 1
A 2018 study reported household expenses on drinking water. **(A)** The poorest respondents paid the highest marginal cost for drinking water, while **(B)** households with the highest Water Insecurity Index paid the most. **(C)** Interestingly, relative household expenses increased with education level, suggesting that with higher education, people are willing to spend more on safe drinking water for their families. Cropped from the original figure by Shrestha et al. (2018) and shared under Creative Common license CC-BY.

FIGURE 2
Tatirano Social Enterprise operates a network of 100 community rainwater harvesting systems serving 25,000 people in southern Madagascar (https://tatirano.org/). Understanding the importance of involving women in leadership roles, Tatirano hires female Kiosk Agents who operate the community water points. Here, Agents are sharing experiences from their kiosks during a meeting at the Tatirano head office in Fort Dauphin (Fort Dauphin, Madagascar, 2022, copyright Karl Zimmermann). Permission obtained from participants prior to photo capture.

3.3 Water changing livelihoods

> "*In general economics, there is a trade-off between efficiency and equity; water is the opposite, where inefficiencies lead to the inequities*" -H.E. Shanmugratham (Singapore).

Mr. Shanmugratham's quote explains that since water weaves into so many aspects of industry, health, food security, leisure, and culture at the same time, the typical economic levers may not suffice to understand and sustainably manage water and support those whose livelihoods depend on it. In fact, the 2016 UN-Water Development Report estimated that 1.4 billion jobs (42% of world's workforce) are *heavily* water-dependent and another 36% are *moderately* water-dependent (United Nations world Water Assessment Programme and UN-Water, 2016); from agriculture and fishing to mining, aquaculture, power generation, forestry, water supply and sanitation, healthcare, tourism, and manufacturing. By 2050, water stress could affect 45% of global GDP and 52% of the world's population, particularly farming communities (Rosegrant et al., 2002). For example, the Colorado River which serves 40 million people and

FIGURE 3
Water resilience is about treatment technologies but also working with nature and respectfully engaging communities. Here, Juan Pablo from the Fundacion Red Proyecto Gente shares maintenance training with Leonor Bautista about her new biosand filter in northern Colombia (San Vicente de Chucuri, Colombia, 2023, copyright Karl Zimmermann). Permission obtained from participants prior to photo capture.

farms in the U.S. and Mexico faces a 9% decline in flow for *each* 1°C of warming (Fleck and Udall, 2021).

Despite these challenges, opportunities exist. In sub-Saharan Africa, less than 30% of rainfall is effectively used by crops (Rockström et al., 2010), but new irrigation techniques (Bwambale et al., 2022) along with improved water management offer potential. Climate-resilient industries are diversifying water sources, with trends in water reuse and rainwater harvesting. For instance, mines in the Chilean Andes use desalinated seawater to preserve groundwater for local communities (Toro et al., 2022) and an NGO in Madagascar collects rainwater to sell as low-cost drinking water[2] (Kelly et al., 2023). In 2010, up to 20 million hectares of land were irrigated with wastewater (Jiménez et al., 2010), including 70,000 farms near Mexico City where lands with wastewater access are rented at two-to three-times higher rates (Jiménez and Asano, 2008), exemplifying how the local economy places a significant economic value on having access to this water resource and how localized innovation for water management can support livelihoods.

3.4 Water shaping culture

Water scarcity can impact livelihoods by forcing new cultural norms like the emergence of "water wives." In Denganmal village, Maharashtra, India, women may walk 8–12 h daily to fetch water and government water tanks are often insufficient (Kaur, 2022). The strain of providing water for their families has led some to turn to polygamy: when a man marries more than one woman, his home has more capacity to fetch water. Kaur (2022) reported specific roles are assigned to each wife, whether to collect water, cooking, or childcare. Water wives reinforce social oppression toward women and girls, leading them to postpone education to fulfill duties as "wife." The second and third wives, often from marginalized background, are valued primarily for their labor, and "*her identity is reduced to merely being a commodity.*" Water scarcity has seemingly led to the acceptance of polygamy in local cultures of this area, providing marginalized women an escape from traditional taboos around being unmarried, but raising critical concerns associated with the social and personal implications.

4 Resilience in every drop: opportunities for a resilient water future

"Some framings of water resilience are focused on the built environment, for example, treatment plants and distributions systems, but we also know that resilience is about the ability of communities to continue to access clean and safe water." At the WEST Water Conference, Lucy Rodina[3] noted that a resilient water future is more than just about technologies, but also about the adaptive capacity of communities (Rodina and Chan, 2019). From these learnings, we propose that our resilient future water systems will comprise three elements, which are applicable to developing and developed communities alike: 1. Resilient technologies, 2. Working *with* nature, and 3. Respectful engagement with communities (Figure 3).

4.1 Resilient technologies

4.1.1 Technologies for water monitoring

The water treatment field came into the light in 1854 when John Snow compiled public health records to map the source of a London

2 https://tatirano.org/

3 Lucy Rodina is an Adjunct Professor at the University of British Columbia and a Senior Policy Advisor at Environment and Climate Change Canada.

neighbourhood's cholera outbreak: a hand pump infected by a nearby leaking water closet (Zimmermann, 2023). Today, water treatment and environmental stream flows are monitored in real-time, while wastewater monitoring enabled the detection of SARS-CoV-2 outbreaks (Polo et al., 2020). Such data is resource-intensive to gather, restricted to within existing networks and offers mostly reactive responses. Our future water systems will build resilience by proactively predicting upcoming water states.

Proactive management can require watershed-scale monitoring, increasingly relying on satellite data and remote sensing. NASA's GRACE mission tracks groundwater by measuring the distance between orbiting satellites affected by groundwater's gravitational pull. Despite limited spatial resolution at small scales, researchers using GRACE data found that 56% of the world's major aquifers are being depleted (Richey et al., 2015). Satellite imagery also tracks chlorophyll-*a* levels in European lakes, indicating freshwater eutrophication trends (Bresciani et al., 2011). Elsewhere, researchers employing remote sensors on community water points and infrared precipitation measurements reported that handpump usage was inversely related to local rainfall (Thomas et al., 2019). They later used machine learning to predict waterpoint functionality in consideration of precipitation and surface water availability (Thomas et al., 2021). Emerging technologies like these enable us to understand watershed-level water quality, availability, and even society's interactions with water, enabling a proactive approach to water management.

4.1.2 Technologies for water treatment

For centuries, wastewater treatment aimed to protect the environment; future systems must also emphasize resource recovery. Zheng and Blair[4] (Metro Vancouver regional government, Canada) envisioned "*There are resource recovery options in wastewater, like biogas capture, fertilizers, and effluent heat recovery that can help Metro Vancouver become carbon negative.*" Carbon-negative wastewater treatment aligns with national carbon goals, addressing the 3% of global industrial CO_2 emissions from the water industry (Edenhofer et al., 2014). Resource recovery can reduce reliance on imports and environmentally-degrading resource harvesting. For example, cation exchange resins enable selective nitrogen adsorption to recover ammonium from wastewater for fertilizer, skipping the energy-intensive denitrification and Haber-Bosch processes (Clark et al., 2022). Nanocellulose in wastewater can be recycled into materials including bathroom tissues, although the researchers surmise the uncertain public acceptance of recycled toilet paper (Espíndola et al., 2021). In the Netherlands, NEREDA Aerobic Granular Sludge systems produce precursors to Kaumera biopolymers (Felz et al., 2016). As an alginate substitute, Kaumera has applications from self-healing concrete to controlled-release fertilizer (Estévez-Alonso et al., 2021). Whether harvesting carbon, ammonia, or cellulose from wastewater, we advocate for nutrient recovery and the shift in approach from "waste-water" which necessitates treatment, to "resource-water" which allows for mining.

4 Dana Zheng is a Program Manager, Source Control Policy, Liquid Waste Services at Metro Vancouver and David Blair is an Assistant Project Engineer, Collaborative Innovations, Liquid Waste Services at Metro Vancouver

Technological advances in drinking water treatment are also enabling new paradigms in water management, especially around potable reuse. Addressing water and political insecurity, Singapore's NEWater scheme uses an indirect potable approach, mixing treated wastewater with rainwater before further treatment. This program provides a cost-effective alternative to desalination that meets 30% of demand during droughts and decreases demand on water imports (Lee and Tan, 2016). Similarly, the Orange County Water District's (U.S.A.) potable reuse scheme involves microfiltration, reverse osmosis, and advanced oxidation. However, public perceptions are crucial: Dolnicar et al. (2011) found that 38% of respondents viewed recycled water as "disgusting" and 48% disliked its taste. Importantly, Rice et al. (2016) showed awareness of water reuse increased support and so education is key to acceptance and the implementation of future water technologies.

4.2 Working with nature

Drafting from his kitchen table in 1893 at a time when London air was choked with smog, invasive odours emanated from the streets, and urban sustainability was barely an afterthought, Ebenzer Howard devised the Garden City Movement. Stanley Buder contextualizes Howard's thesis as Buder (1990): "*Dismissed by reviewers as the utopian fantasy of a naïve enthusiast, [Howard's] deceptively simple concept has provided a basis for modern city planning's most elusive quest, the environmental design of the ideal community.*"

A century later, municipalities are implementing "Blue-Green City" strategies, leveraging nature-based solutions to bolster urban water management, biodiversity, energy efficiencies, and citygoers' connection to nature. After generations of attempts to out-engineer the forces of nature, today's societies are working with nature. Daylighting urban streams involves re-opening buried waterways, benefitting urban landscapes with stormwater management, urban heat management, aquatic habitats, and opportunities for water education, not to mention beautiful greenspaces (Khirfan et al., 2020). We highlight daylighting examples from the Cheong Gye Cheon river in Seoul (South Korea), Zürich (Switzerland), and Spanish Banks Creek in Vancouver (Canada) (Figure 4). The latter project proved beneficial in 2021 when Vancouver was inundated by rain. The watershed draining into Spanish Banks Creek fared better than surrounding areas suffering road washouts and erosion. Additionally, a Vancouver gradeschool class now releases salmon fry into the stream and in the past years, hundreds of fish returned to spawn, an example of the often-overlooked benefits to biodiversity and education opportunities of blue-green infrastructure.

Answering to the need for watershed-scale planning, tools are emerging to help municipalities understand their opportunities for blue-green infrastructure. UrbanBEATS is a model incorporating urban planning and stakeholder preferences toward stormwater management (Nguyen et al., 2022). UrbanBEATS was applied in Christchurch (New Zealand), generating 1,000 stormwater harvesting layouts for each of multiple climate scenarios, incorporating objectives like neighborhood-scale options with sufficient volume for 30% potable water substitution. The model options varied by neighborhood based on geography, density, demand, space, and existing water systems, and provided starting point recommendations for water leaders to pursue informed and climate-resilient stormwater management.

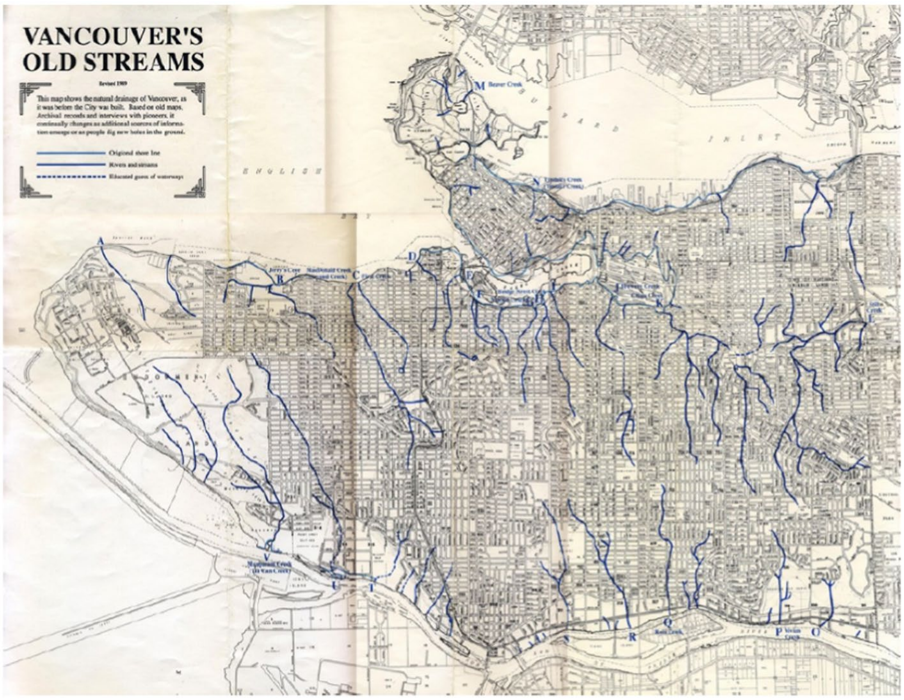

FIGURE 4
In their 1978 map, Sharon Proctor depicts the lost streams underneath the urban landscape in Vancouver, Canada. Spanish Banks Creek is second from the top left. Urban waterways allow people to engage with their environments, and such maps are important for city planning as municipalities seek to work with nature for water management. Reprinted from *"Vancouver's Old Streams, 1880–1920"* by Proctor and Lesack (1978) and shared under Archived Open Data Licence, http://hdl.handle.net/11272/IKHNQ.

4.3 Engagement with local communities

> *"Today, private properties depend largely on public infrastructure to manage onsite rainwater. In the future, as part of more cost-effectively managing citywide rainfall, private properties and infrastructure will play an important role in reducing discharge to the pipe system through onsite actions"—Vancouver (Canada) Rain City Strategy.*

Vancouver's Rain City Strategy (RCS) (Conger et al., 2019) marks a shift from large-scale government management to smaller-scale water systems, like what author David Sedlak described as the fourth evolution in water management (Sedlak, 2014). This approach aims to enhance resilience, equity, and sustainability, with private properties playing a key role. Engaging local communities can leverage generations of local knowledge and build resilience by encouraging private investments in water infrastructure and enhancing household adaptability. However, decades of large-scale urban water management have disconnected many people from their water sources.

We envision three steps to empowering people towards water management. First, creating *awareness* regarding the local water challenges: drought in their watershed, neighborhood flooding, or drinking water contaminants. Second, *education* on sustainable water future: water reuse, blue-green infrastructure, or household water management. Finally, people need *resources* to implement their chosen water solution: financial, regulatory permissions, and technical support. Once empowered for water action, communities are motivated to participate in water management.

At the 2022 WEST Conference, Madjid Mohseni[5] drew on decades of experience building water partnerships with First Nations communities when he shared, *"Communities want to be involved, they do not want to be told what the answer is. They want to operate their water systems. And they want to take the ownership and share their success and experiences. We need to change our mindset […] towards building coalitions with community in the centre."*

5 Conclusion

Inspired by discussion at the Water and Environment Student Talks (WEST) Conference, this article linked changing climates and water security with emphasis on human experiences:

1 New technologies enable proactive approaches to adapt to changing water resources and can turn *waste-water* into *resource-water*.
2 Resilience is achieved by working alongside nature, embracing blue-green infrastructure, and collaborating with natural water entities.
3 These approaches to water-resilience are possible only by working with communities.

5 Madjid Mohseni is a professor in Chemical and Biological Engineering at the University of British Columbia and the Executive Director of RESEAU Centre for Mobilizing Innovation.

Changing climate is affecting communities worldwide and it is through water that society feels the effects of climate change. By working together, we envision a future where water once again represents the shark's supporting environment and not its teeth.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

Author contributions

KZ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. CS: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. VK: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. SK: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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